Chapter III
Navigating a Speckled World: Interacting with Wireless Sensor Networks

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ABSTRACT

The Speckled Computing project is a large multisite research project based in Scotland, UK. The aim of the project is to investigate, prototype, and produce tiny (1mm$^3$) computational devices, called Specks, that can be configured into wireless sensor networks, called SpeckNets. Our particular interest is in how people might interact in such environments, what interaction tools they require, and what characteristics are required to be provided by the operating system of the Specks. Interaction in these environments places the human physically inside an information space. At one time, the human may be interacting with one Speck, at another with a hundred, and at another with several thousand. Moreover, the Specks themselves have no input method, apart from their sensors, and no output display. We explore these issues through taking some theories of distributed information spaces, some design principles from information visualization, and report on some empirical studies of prototypes and simulations that have been developed.

INTRODUCTION

We are interested in human interaction with a new type of information space, one that involves computer miniaturisation, sensors, wireless communication, and networking. Devices are on the verge of reaching a critical point of size and affordability that will allow them to be embedded in our environment in their thousands, sensing their surroundings and opening up a broad range
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of new applications. They will also be embedded in clothing and jewellery, truly becoming part of the fabric of the world. It is a vision that was foreseen by Mark Weiser (2002), who coined the term “ubiquitous computing”; but it is likely that even he would be astounded at the miniaturisation of technology that has made his prediction possible, in projects such as SmartDust (Hoffman, 2003), and more recently the Speckled Computing Consortium (2006).

The vision of Speckled Computing is the development of miniature 1mm³ computational devices (Specks), which will be simple, small, and cheap enough to be distributed in their thousands (Arvind, 2005). They will combine wirelessly to form a unique class of wireless sensor networks (WSN), called SpeckNets. Some SpeckNets will be embedded in the fabric of buildings, but others will be spontaneously created by scattering Specks over an area or even spraying them onto surfaces. The combined storage and processing of the microchip revolutionised computing in the late 20th century. Specks, offering combined processing, storage, sensing, and communications, are expected to revolutionise computing in the 21st.

The characteristics of SpeckNets give rise to some specific requirements for human-SpeckNet interaction. First, the invisibility of the Specks and the lack of any perceptible output mechanism means the human-Speck interface must be provided through some other mechanism. Second, people may literally be immersed in the network surrounded by Specks, of various types in various configurations, in three dimensions; they are not interacting with a device, they are inside an information space. Third, the SpeckNet may not know about the physical characteristics of the real world. In stable SpeckNets, it would be possible for the network to develop a model of the world and relate this to its own configuration. However, in recently created or in movable SpeckNets, the human will have to supply information about the physical world. Finally, there is the issue of scaling interaction from individual Specks to potentially thousands.

Previous work on WSNs and human interaction with these networks identifies a number of different types, depending on the method of deployment of the nodes, their size, the communication mechanism, and the network’s topology (Romer & Mattern, 2004). There have been many WSN applications, each with its own interaction methods and techniques. For example, a sensor network has been embedded within a vineyard. The system would automatically trigger an event, such as turning on sprinklers when soil moisture is low or firing air cannons when birds were detected (Burrell, Broke, & Beckwith, 2004). Another example is the self-healing minefield (SHM), a minefield that can reorganise itself (through mobile mines) to cover gaps that appear (Meriall, Newberg, Sohrabi, Kaiser, & Pottie, 2003). ARGO is a global network with an intended 3,000 sensors that will monitor salinity, temperature, fresh water storage, and so forth, of the upper layers of the oceans, and transmit results via satellite. Deployment began in 2000, and as of February 2006, 2,385 floats were in operation (Argo Project Office, 2006). In most of these applications, data was sent from the network to a remote database.

In contrast, we are interested in WSNs where the person is inside and interacting with the network directly; SpeckNets. We describe a generic tool-kit for humans interacting with SpeckNets, focusing specifically on the unique characteristics that separate them from other WSNs. In the next section, we elaborate on the requirements that this interaction demands. This is followed by some background theories that have helped to shape the tools. Some studies of alternative designs are described that help to evaluate the effectiveness of both theory and tools. The chapter closes with some conclusions and indications concerning the future of interaction in WSNs.
REQUIREMENTS

The aim of our work in the Speckled computing consortium is to explore the requirements of human-SpeckNet interaction (HSI). One reason for doing this is to inform the design of the operating system that will be developed for the Specks. Another is to elaborate on possible scenarios and applications.

A typical scenario of HSI could be a surveyor performing an inspection on a domestic building. The surveyor would arrive at the house and be alerted that he or she has entered a SpeckNet. As part of the initial detection, the interaction tool will have initiated a harvest of top-level information, such as the types of sensors in the network, date of installation, and so forth. The surveyor would be presented with this information and then make a decision as to whether or not this information is valuable.

The surveyor may be interested in the SpeckNet’s ability to supply moisture information, and initiate a harvest for values from moisture sensors over a certain threshold. This information would be retrieved and presented along with metadata (e.g., time of last reading) and new options (e.g., hourly readings available for last three weeks).

Having identified an area in the network that is of interest, the surveyor would be guided to the appropriate room to view the information. At this point the surveyor may interact with the representation to gain a better understanding (e.g., rate of spread, severity, etc.). This investigation may initiate a new search for more information.

This scenario captures many of the characteristics of HSI. The network will initially require detection. The user will not necessarily know the location extent or other characteristics of the network. Detection is concerned with ensuring people know that they are in an information space, and how they know what is connected to what.

The user will also be concerned with finding out what information is available from the information space, how it is distributed, and how to control the harvesting of the content. As a real-time system, it would be infeasible to work with all of the data. Instead, the user will control the nature of the data harvested, making it dynamic and user-driven.

The user needs to know what types of Specks there are in the SpeckNet, what attributes they have, and what the values of those attributes are and can be. Whilst this data is of a limited range (since Specks have a limited number of sensors), the data may have other attributes, such as when it was collected.

One consideration is the best way to present information. A visualisation is one way, but auralisation is another. Since the user may be fully immersed in the network in three dimensions, the presentation needs to make them aware of the scope of the network. Presentation of the details of the individual Specks and groups of Specks is also needed. The relative position of the user to any particular piece of data is required so people can find their way to a specific physical location.

As they are so small, Specks cannot have their own display other than perhaps a light. This is clearly inadequate to provide details of the sensor states and readings over a period of time, and so we must find an alternative.

Increasingly developers of WSN applications are beginning to understand the benefit of displaying sensor readings in a real-world context. Although due to the tradition of viewing data remotely, a virtual environment is often used to represent the real world with the sensor data overlaid. An early example was the fire alert system reported by Boone (2004), where sensors attached to trees in a forest could detect fires, and display the location in a 3-D GIS-based virtual environment. The benefit of the system was the ability to use the map to coordinate fire crews tackling the fire. A more recent system combines real-time sensor data (including meteorological readings as well as live audio and video) with the Google Earth application to allow an environment to be monitored remotely by anyone with
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an Internet connection (University of California, 2006). The ARGO project now also allows the tracking of its sensor buoys using Google Earth, but they are yet to integrate the sensor readings into the application.

The intended miniature dimensions and large numbers of Specks mean that they will blend into our surroundings to the point where they are indistinguishable from it; floors will store data on human traffic, machines will store data on their operational performance, buildings will store data on conditions, such as dampness within their walls. Our physical environment will be coated with a layer of data, with no fixed point of interaction; instead, a person will interact directly with the object they want to gain information about.

The combined requirement for possibly complex information tied to devices too small and numerous for individual interfaces makes the use of augmented reality (AR) a natural choice for HSI. A live video stream can be enhanced with computer-generated objects (rendered so that they appear to be within the actual scene) and then presented to the user. We have not explored immersive displays in our work, preferring to use non-immersive displays, as have been tried elsewhere, including computer monitors (Belcher, Bilinghurst, Hayes, & Stiles, 2003), PDAs (Wagner & Schmalstieg, 2003), and mobile phones (Moehring, Lessig, & Bimber, 2004).

The single largest technical issue remaining in augmented reality is that of accurately aligning the real and virtual environments, a process called registration (Azuma, Baillot, Behringer, Feiner, Julier, & MacIntyre, 2001). A number of systems allow the technology used for performing this registration to also offer 3-D input. A notable example is the ARToolkit (HitLab-Washington, 2006); a software library that includes facilities required to optically track images placed in the real world, and align computer-generated graphics based on their position and orientation.

Figure 1 shows how ARToolkit has been used in our previous work to both allow the alignment of 3-D geometry with real objects (in this case playing cards), as well as tools for interacting with the AR representations (in this case a proximity selection paddle). Like many researchers, we continue to use ARToolkit to allow us to focus on issues of interaction, rather than the technical issues of implementing a working AR system.

NAVIGATING INFORMATION SPACE

There are a number of conceptualisations of human-computer interaction that foreground the distributed nature of information spaces. Benyon (2001; 2005) highlights how information is distributed both physically and conceptually, and this leads to the need for people to navigate the information space. These ideas have been applied to Web site design (Benyon, 2006). Wright, Fields, and Harrison (2000) present a model of distributed information spaces, called the resources model, in which they focus on information structures and interaction strategies. Distributed cognition (DC) similarly argues that people make use of resources in the world as a central part of their cognitive activities (Perry, 2003), as does situated cognition (Lave, 1988). There are also similarities with Pirolli’s “information scent,” where people

Figure 1. Paddle selection in Yu-Gi-AR
are seen as “informavores”; utilising our evolved food-foraging mechanisms for information gathering (Pirolli, 2003).

In information foraging theory, people shape their behaviours according to the information ecology. Information foraging theory shows how cognitive and perceptual abilities lead to information finding. Information scent (e.g., good labelling) is concerned with proximal cues by which to judge distant information sources. Optimal foraging is the trade-off between finding, choosing, and handling information.

DC foregrounds the importance of cognitive artefacts such as checklists, books, and diaries, and how they are distributed across an environment and are fundamental to cognition (Perry, 2003). DC is concerned with knowledge in the head and knowledge in the world (Zhang, 1997). The resources model (Wright et al., 2000) identifies some specific type of knowledge that designers can place in the world such as plans, histories, and action prompts.

In the navigation of information space approach (Benyon, 2001; Benyon, 2005; Benyon, 2006; Benyon & Höök, 1997), lessons from environmental psychology and urban design are used to inform the design of information spaces. Techniques, such as developing maps, guides, signposts, and landmarks, help people to develop both survey knowledge of the space and route knowledge to help them move through the space.

Three activities are highlighted by the approach. Wayfinding is concerned with how people reach a known destination. Exploration is concerned with finding out about the size and topology of a space. It is concerned with establishing a horizon, and how one part of the environment relates to others.

A third activity that is undertaken in information space is object identification. Here people are less interested in the location of objects, or finding a path, or reaching a goal. Object identification is concerned with finding categories and clusters of objects spread across environments, with finding interesting configurations of objects, and finding out details about the objects.

The human interacting with a SpeckNet is physically inside both an information space and a physical space. People have to physically move through the physical space in order to select the part that interests them. They must also understand the information that is available in the SpeckNet and how it is distributed. We frame our discussion in terms of object identification, exploration, and wayfinding in information spaces.

Figure 2 shows the sequence of these activities in the context of human-SpeckNet interaction. The process begins at the exploration stage, gaining an understanding of the data distributed through the SpeckNet. Having chosen sensor readings of interest, the user moves (wayfinding) to reach the real-world location where they were generated. At the object identification stage, the user attempts to make sense of the data in the context of the environment. If satisfied, then the user can move onto other tasks; but if more information is required, then the process is repeated, leading to a spiralling pattern as they drill-down into the information space.

The actual tasks at each stage of the model could range widely, from complex to trivial. Ex-

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Figure 2. Model of Human-SpeckNet Interaction
ploration may require the comparison of thousands of data values, or a single one; wayfinding could require crossing a city, or simply turning around to deal with data behind you; object identification could require a user to cross-reference information from several different regions, taking into account the context of the environment and decades of professional experience, or simply being shown which switch to flick. However, despite the huge range of scenarios, the sequence is seen as fundamental to human-SpeckNet interaction.

Three main studies have been undertaken that explored principles of supporting users in HSI. The Specktator investigation explored user interaction issues within a small-scale SpeckNet, using hardware prototypes. A group of users carried custom-built Speck devices (a Specktator) that monitored their level of activity (through a pedometer) and visits to designated locations (via Specks distributed in the environment). Two groups of four people took part in the investigation, carrying the Specktator devices for a period of 3 hours. At the end of each trial, the participants regrouped and were presented with visualisations of the data collected.

The AR HomeFinder investigation explored information visualisation techniques in an augmented reality setting. A tablet PC (in essence, a 10.4” flat panel screen with a computer built into it) was used in conjunction with a Web cam to produce a handheld AR window. This allowed a virtual representation of houses to appear on a tabletop, which 20 participants (12 male, 8 female) then explored in three tasks. The focus of this work was on the selection of objects via a pen on the screen, or by targeting the camera (gaze method) and on adjusting parameters again via the pen and then by using the motion of the camera to interact. The study also explored providing an overview of the data through glyphs.

The virtual warehouse investigation explored the requirements for wayfinding tools (as well as the requirements for a SpeckNet to support them), using a virtual environment. Two wayfinding tools were compared (using waypoint markers and using relative positioning), and presented to the participants in a random order.

**OBJECT IDENTIFICATION**

In an information space, people need to find out what objects exist, their attributes, and what the values of these attributes are. Our experience with the object identification issues in SpeckNets comes from the Spektator and AR HomeFinder investigations.

For the Spektator, the chosen scenario was for each Speck device to function as a virtual pet, where its appearance would reflect the underlying data (see Figure 3). A semantic relationship was chosen where, for example, encounters with a Speck placed in a kitchen area would affect the appearance of the character’s torso (from thin to fat), walking activity would affect limb size, and visits to a print room would affect head size (which assumed printed documents would be of an intelligent nature).

The decision to convey context via a feature and representation of a data value via the appearance of that feature is based on the work of Chernhoff, who used faces to represent chemical samples (Chernoff, 1973), and Spence, who used glyphs for both house and ship representations (Spence, 2001). The aim is to present a recognisable link between appearance and underlying data.

*Figure 3. Specktator character representation*
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Although the study was small in scale, the results were promising, in that the semantic relationship proved easily understandable. Although perceived accuracy of the representations was low, and indeed it would have been impossible to view a character and determine, for example, how many trips had been made to the kitchen, the purpose was for comparison and for this, the visualisation seemed appropriate.

The AR HomeFinder investigation also explored the use of glyphs. Two types of glyphs were used as shown in Figure 4; simulating the potential for different types of Specks. House glyphs represented three values (number of bedrooms, size of garden, and cost of property), and school glyphs represented two values (number of students and pass rate). In the representation, there were 18 houses and 4 schools shown in an area approximately 25cm x 25cm.

Part of a questionnaire, presented during the trial, asked participants what they expected the components of each glyph to represent. Results show that a literal mapping, such as tree size conveying size of garden, could be intrinsically understood (chosen by 19 out of 20); but an abstract mapping, such as platform height for price, was less obvious (correctly chosen by 12 out of 20).

Participants were capable of identifying extreme values (e.g., most expensive house) almost immediately; even if a subsequent search was performed to confirm their initial choice. However, identifying actual values was still problematic, and so it is clear that some method of obtaining detailed values must accompany a glyph system; the most obvious of which is to allow selection of a glyph and present its values.

The selection task in the AR HomeFinder application required participants to find a house of a given price from the 18 presented. Two types of interaction were explored. A gaze interaction required the user to centre the camera on an object. After a few moments, the camera would zoom in to provide details. A pen interface required the user to tap on the object to initiate the zoom function.

The task was performed twice using a pen (or stylus) to select objects on the tablet PC, and then twice more using the camera to target the AR houses (termed gaze selection). Figure 5 shows the task completion times for the four repetitions, and it is clear that although initially poor performance (Gaze1), the gaze selection method quickly improved. However, despite promising results, the gaze interaction was not well received, being reported as both harder to select buildings, and harder to remember which buildings had been checked. In addition, 14 participants preferred the pen method against 4 that preferred gazing.

Figure 4. Example glyphs from AR HomeFinder
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Figure 5. Comparison of selection methods

EXPLORATION

In some SpeckNet applications requiring human intervention, the data interpretation phase may be trivial, in that the network need only identify the point of intervention (e.g., directing firefighters to a fire). In other applications, the user may need to perform some exploratory analysis (e.g., the ALife system described by Holmquist, Gellersen, Kortuem, Schmidt, Strohbach, Antifakos, Michahelles, Schiele, Beigl, & Mazé, 2004, where the user must prioritise trapped avalanche victims). While the results reported for object identification show how individual Speck values can be interpreted; they do not address the large potential scale of data that may be presented.

The problem is, in essence, one of applying information visualisation principles to an AR environment. Specifically, the principles of overview, zoom, and filter, which were proposed as fundamental by Shneiderman (Card, MacKinlay, & Shneiderman, 1999). The second part of Shneiderman’s mantra, details on demand, is covered by our category of object identification. These issues were considered in the second and third stages of the AR HomeFinder investigation.

Creating a semantic relationship between the underlying data and the glyph representation is particularly important in enabling users to develop an overview of the data. Lee, Reilly, and Butavicius (2003) report that glyphs perform poorly when compared to spatial visualisations, which they attribute to the glyphs being read sequentially (that is, each consulted in turn until the required one is found). Our contention is that a semantic link creates visual cues or, following the metaphor of information scent, an aroma that can be recognised much more easily.

Some support for this position was presented in the object identification section, where we reported that participants in the third stage of the AR HomeFinder investigation could identify extreme values almost immediately (i.e., not sequentially searching to find them). In addition, participants were given additional tasks of identifying trends (similarities) and exceptions to those trends, and again it was observed that the majority were initially drawn to the correct objects.

An interesting observation relating to identifying trends is that, for example, the question “Identify a group of 1 bedroom houses” is open to interpretation as to what constitutes a group. Figure 6 shows the layout of houses on the map used, and circles with letters are one-bedroom houses. Five participants only identified the A’s as constituting a group, while the remainder
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included B, with the exception of one individual who marked all.

The second stage in the AR HomeFinder study explored another tool in exploration, the use of dynamic filtering to focus attention. Participants were given a range of prices and asked to report the number of houses that were within this range. First, they used a standard dynamic filter scroll bar using the pen, and then a novel method of using the camera to interact. The inspiration for the second method came from Beardsley, Van Baar, Raskar, and Forlines (2005), who used the tilting of a projector to control scaling of an image.

The principle of the interface is shown in Figure 7, and consists of two components on the tablet PC screen; the selection rings and dynamic filter range bar (left). The image on the right shows the interface in use. The selection rings are fixed in 3-D space, and so, movement of the camera allows the user to left or right rings, to adjust lower or upper boundaries respectively. Actual adjustment of the value is achieved by tilting the tablet PC to the left or right, moving the parameter range to the left or right in turn. Tilting to a more extreme angle causes the parameter to adjust at a more extreme rate.

Participants were comfortable using the point-click method and were both fast and accurate in completing tasks (only one participant gave an incorrect answer, which was due to mishearing the range values). In contrast, the tilt interaction method performed very poorly, taking over twice as long to use, had three non-completions and three incorrect responses. Many design lessons were learnt that could improve the tilt interaction method, but it is unlikely to match the ease of use found from point-click interaction.

WAYFINDING

While the previous sections lay out a foundation for interacting with SpeckNet data from a region directly in front of the user, they may not always begin adjacent to it. Since the points of interest are generated from sensor readings, they could occur anywhere within the SpeckNet; and since we are interested in individuals interacting with these points directly, additional tools are required to guide them to the locations. The majority of our understanding in this area comes from the Virtual Warehouse investigation (shown in Figure 8).
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Directing someone to a particular area of interest within the SpeckNet is problematic since we cannot assume that they have previous knowledge of the environment. As such, some sort of navigational aide is required to direct them towards the destination. In contrast to the majority of existing guidance applications (e.g., GPS road guides), a SpeckNet is not expected to easily have access to global environment information. It is expected that the network will be able to generate knowledge of its own distribution, but will have limited knowledge of non-Speckled entities, and also limited knowledge of an environment’s permeability to humans (i.e., the paths by which a person can move through the environment).

The first guidance tool tested was the familiar waypoint system used in the majority of navigational systems (in one form or another), where the user is given a sequence of points to pass through. The second method provided the user solely with relative information of direction and distance, which is the minimum information expected to be available from the SpeckNet (see Figure 9).

Figure 9 shows a comparison of the wayfinding times (i.e., from starting point to goal) for each of the collection conditions (W for waypoint, R for relative). The six paths are arranged from the most simplistic on the left (a short distance with one wall obstructing), through to the most complex on the right (longer distance with several intervening walls and different vertical level). In each pair, the result from using the relative system is shaded to aid comprehension.

The most noticeable result is that use of the relative system always resulted in a wider range of collection times than the waypoint system. In runs 1, 2, and 3, for example, the times were found to not be significantly different statistically, but it is clear that some individuals performed significantly worse using the relative system. And indeed, the average standard deviation for the relative system over the six runs was twice that of the waypoint system.

Runs 2 and 3 included unexpected blockages, which led to the increased collection times, and also less difference between the waypoint and relative systems. This is to be expected, since the waypoints did not take into account the blocked paths (simulating the intrusion of an object that the SpeckNet is not aware of), participants were forced to deviate from the path and find their own route, as with the relative system. This shows that although substantially superior, the benefits of the waypoint system could easily be compromised if the paths that it believes exist become blocked.

Table 1 shows the results of T-Tests comparing the waypoint and relative collection times for each run. Note that generally speaking, the difference becomes more significant (closer to zero) as the paths become more complex. The notable exceptions are runs 2 and 3, which as mentioned previously, is attributed to the inclusion of blockages removing the benefits of waypoints.
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However, despite the better performance of the waypoint system, we should not forget that the participants did still manage to reach the goal using the relative system. Therefore, the main conclusion from these results should be that it is possible to navigate using only relative information, but with penalty increasing over distance.

CONCLUSION

Our work on human-SpeckNet interaction has answered several specific questions about this particular type of HCI, and has raised some more for future forms of interaction. Wayfinding in SpeckNets is assisted by providing waypoints. Exploration is supported by providing an overview of the whole space, and the distribution of different types of Specks and different values for the attributes of Specks. Object identification is supported by having clear, semantic representation of attributes and their values.

The recommendation for waypoints in SpeckNet applications is not necessarily straightforward. Ideally, all applications would use them because of the proven benefits they offer, but there is the issue that their implementation has a cost. Either the SpeckNet itself must generate paths or they must be set manually by an operator, which has processing or manpower costs, respectively. As shown in the Virtual Warehouse study, if there are unexpected barriers, then this cost could be paid with no benefit. As such, the recommendation is dependent on the application. If there are substantial horizontal and vertical barriers (such as in a building) then waypoints are almost certainly required, but if not (as an extreme example, a SpeckNet embedded in a sports field to monitor the turf) then a relative system could suffice.

The huge difference for split levels suggests that performance gains could be achieved by using floor level indicators. Obviously, this would be an added feature, requiring additional resources, but offering rough location information could be a compromise between the two tested systems.

Table 1. Statistical comparison of waypoint and relative system collection times. A value of less than 0.05 is considered to be significant

<table>
<thead>
<tr>
<th>Run</th>
<th>T-Test probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2434</td>
</tr>
<tr>
<td>2</td>
<td>0.6003</td>
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</tr>
<tr>
<td>5</td>
<td>0.0012</td>
</tr>
<tr>
<td>6</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

Figure 11. Collection times in Virtual Warehouse

![Figure 11. Collection times in Virtual Warehouse](image)
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The results also confirmed the use of glyph representations as an ideal solution for SpeckNet data (encoding both data type and value, easy interpretation through use of semantic links, etc.), and so the general tools for querying an environmentally distributed database were identified. However, some shortcomings were also identified, namely, that data outside of the field of view was often overlooked.

It is likely that the poor feedback on the gaze selection was due to participant’s overall perceived performance and unfamiliarity. The results indicate that it is a promising method, and it is hoped that users would become more comfortable with it through use.

In contrast, attempts to adjust parameter bounds using camera interaction were largely unsuccessful. Gazing may have performed better because it is a natural Human activity in the real world; looking at something you are interested in. Adjusting values is a less natural task, and so better suited to other form of interaction (either screen based or physical widgets).

Of course, there will be many novel devices, visualisations, and other displays designed to optimise performance in particular types of environment. However, we are seeking something more generic; the types of tools and widgets needed to support basic human-SpeckNet interaction. Primarily, this will be implemented on some personal device that mediates interaction with the SpeckNet, but the design principles also need to be supported by the operating system and data structure of Specks themselves.

A number of features of Specks and SpeckNets have been identified. Specks need to be able to identify their structure and attribute values in some accessible way, such as an XML description. Specks need some distance measure so that the SpeckNet can generate an overview of the mesh and indicate the network’s horizon. Specks need a way of propagating the relationships between two locations in the SpeckNet, dependent on specific attribute values, so that the person can navigate from one location to another.

Interacting with SpeckNets provides an insight into the range of interaction issues that will arise in the future of pervasive and ubiquitous computing. Firstly, unlike most other forms of HCI, interacting with SpeckNets separates device and display. This issue generalises to other areas, such as context aware applications and other forms of ambient computing, where the smooth transition of an interaction from one device to another is a key requirement.

SpeckNets are also examples of interaction with multiple processors, another departure from traditional HCI. There are potentially multiple levels of interaction as the user interacts with different numbers of processors. We think that our tool-kit will generalise to operate up and down through levels of abstraction. We have begun to investigate issues of immersion in the 3-D of the SpeckNet, but more has to be done.

There are also issues concerned with probing the SpeckNet in different ways. Currently, we just retrieve data from the SpeckNet, zoom, and filter based on attribute values. It would be interesting to explore other methods of probing that depend on the sensors the Specks have. For example, in a Specknet with light sensors, one could probe using a torch, but it is not clear what the functionality of such interactions might be.

Human-SpeckNet interaction is just one of the many new forms of interaction that will become familiar over the coming decades. There are clearly some significant new challenges for HCI, but it is also encouraging to see some of the principles that have evolved over the last 30 years do generalise to the new forms. More natural forms of interaction, such as the gaze zoom, will be developed that emphasise an appropriate “human scale” to the interaction.
REFERENCES


